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Influence of Vegetation Structure and Canopy Cover on Litter Carbon Stock in Traditional Agroforestry Systems

(*Pengaruh Struktur Vegetasi dan Tutupan Tajuk terhadap Cadangan Karbon Serasah pada Sistem Agroforestri Tradisional*)

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ABSTRACT

Traditional agroforestry systems play a crucial role in maintaining ecosystem stability, enhancing the ecological functions of tropical landscapes, and supporting carbon cycling through the accumulation of biomass and litter. This study aimed to analyse the influence of vegetation structural attributes, including tree density, basal area, and canopy cover, on litter biomass and litter carbon stocks in traditional agroforestry systems in Southwest Papua, Indonesia. Data were collected from 30 systematically established sample plots measuring 20 × 20 m in Baingkete and Klayili Villages. Each plot was assessed through vegetation inventories, basal area measurements, canopy cover assessments, and litter sampling. Litter biomass was oven-dried and subsequently converted into carbon stock using the IPCC conversion factor of 0.47. The results showed that the mean litter biomass reached 0.886 kg m^{-2}, equivalent to 8.86 t ha^{-1} of dry litter biomass, resulting in an estimated litter carbon stock of 4.28 t C ha^{-1}. Correlation and regression analyses revealed significant positive relationships between vegetation structural attributes and litter biomass. Basal area exhibited the strongest relationship with litter biomass ($r = 0.79$, $R^2 = 0.62$, $p < 0.001$), followed by tree density and canopy cover. These findings demonstrate that stand maturity and vegetation structural complexity are key determinants of litter production and associated carbon inputs. Therefore, the conservation of multistrata agroforestry systems is essential for enhancing carbon sequestration potential, supporting climate change mitigation efforts, and strengthening carbon accounting initiatives.

KEYWORDS*: *basal area; canopy cover; carbon sequestration; litter biomass; traditional agroforestry

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INTISARI

Sistem agroforestri tradisional memiliki peran penting dalam menjaga stabilitas ekosistem, meningkatkan fungsi ekologis lanskap tropis, serta mendukung siklus karbon melalui akumulasi biomassa dan serasah. Penelitian ini bertujuan untuk menganalisis pengaruh atribut struktur vegetasi, meliputi kerapatan pohon, luas bidang dasar, dan tutupan tajuk, terhadap biomassa serasah dan cadangan karbon serasah pada sistem agroforestri tradisional di Papua Barat Daya, Indonesia. Pengumpulan data dilakukan pada 30 petak contoh berukuran 20 × 20 m yang ditetapkan secara sistematis di Kampung Baingkete dan Klayili. Setiap petak dianalisis melalui inventarisasi vegetasi, pengukuran luas bidang dasar, penilaian tutupan tajuk, serta pengambilan sampel serasah. Biomassa serasah dikeringkan menggunakan oven, kemudian dikonversi menjadi cadangan karbon dengan faktor konversi IPCC sebesar 0,47. Hasil penelitian menunjukkan bahwa rata-rata biomassa serasah mencapai 0,886 kg m^{-2} atau setara dengan 8,86 ton ha^{-1} biomassa kering, dengan estimasi cadangan karbon serasah sebesar 4,28 ton C ha^{-1}. Analisis korelasi dan regresi menunjukkan hubungan positif yang signifikan antara atribut struktur vegetasi dan biomassa serasah. Luas bidang dasar memiliki hubungan paling kuat dengan biomassa serasah (r = 0,79; R^2 = 0,62; $p < 0,001$), diikuti kerapatan pohon dan tutupan tajuk. Temuan ini menegaskan bahwa kematangan tegakan dan kompleksitas struktur vegetasi merupakan faktor utama dalam peningkatan produksi serasah dan masukan karbon. Oleh karena itu, pelestarian agroforestri multistrata penting untuk mendukung mitigasi perubahan iklim dan inventarisasi karbon.

KATA KUNCI: luas bidang dasar, tutupan tajuk, penyerapan karbon, biomassa serasah, agroforestri tradisional.

INTRODUCTION

Agroforestry is widely recognized as a sustainable land-use system in tropical regions, integrating ecological, social, and economic functions through the deliberate combination of perennial woody species and annual crops (Nair, 1993; Leakey, 2014). These systems support rural livelihoods while providing important ecosystem services, including soil fertility maintenance, hydrological regulation, biodiversity conservation, and carbon sequestration (Schroth *et al*., 2004). Structurally complex agroforestry systems frequently resemble secondary tropical forests because of their multistrata canopy architecture, continuous vegetation cover, and efficient nutrient cycling processes. Consequently, agroforestry has increasingly been recognized as an important nature-based solution for climate change mitigation in tropical landscapes.

Litterfall represents a critical ecological process linking vegetation and soil through the transfer of organic matter, nutrients, and carbon (Vitousek & Sanford, 1986). Litterfall constitutes a

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major pathway of carbon transfer from vegetation to soil and plays a critical role in regulating nutrient cycling, soil protection, and long-term carbon sequestration in agroforestry ecosystems (Negash & Starr, 2021; Sari *et al*., 2022). Vegetation structure affects canopy architecture, biomass accumulation, and productivity, which in turn regulate litterfall dynamics and carbon transfer pathways. Through decomposition, litter contributes substantially to soil organic matter formation and long-term carbon sequestration, thereby playing a central role in ecosystem carbon cycling (Kumar & Nair, 2011).

Among vegetation structural attributes, basal area and tree density are frequently identified as important determinants of litter production and carbon accumulation in tropical ecosystems (Turner *et al*., 2022; Ribeiro *et al*., 2026). Larger trees generally contribute greater litter inputs due to higher leaf biomass, greater canopy surface area, and increased biomass turnover rates. Similarly, dense vegetation stands may enhance overall litter production through increased biomass productivity and canopy development. Canopy cover also influences litter dynamics indirectly by regulating microclimatic conditions that affect biomass production, litter retention, and decomposition processes. Recent studies indicate that tree size diversity and stand structural attributes exert stronger controls on carbon storage than species richness alone, highlighting the importance of basal area and canopy architecture in determining ecosystem carbon dynamics (Noulèkoun *et al*., 2023; Alexander *et al*., 2025).

Despite their ecological importance, quantitative evidence linking vegetation structural attributes to litter-derived carbon stocks remains limited, particularly in traditional agroforestry systems. Previous studies have predominantly focused on aboveground biomass and soil organic carbon pools, whereas litter-mediated carbon dynamics have received comparatively less attention. Furthermore, few studies have simultaneously evaluated the relative influence of basal area, tree density, and canopy cover on litter biomass and carbon accumulation within a unified analytical framework. Evidence from eastern Indonesia is especially scarce despite the widespread occurrence of traditional agroforestry systems and their potential contribution to regional carbon budgets and climate change mitigation initiatives.

In Southwest Papua, traditional agroforestry systems are managed under customary land tenure arrangements and are characterized by complex multistrata vegetation structures. These systems are assumed to contribute substantially to ecosystem carbon cycling through continuous litter production and organic matter inputs; however, quantitative assessments remain limited. As a result, their ecological contribution is often underrepresented in carbon accounting frameworks and climate mitigation policies despite their importance for sustainable land management.

To address these knowledge gaps, this study evaluates the relationships among vegetation structural attributes, canopy cover, litter biomass, and litter-derived carbon stocks in traditional agroforestry systems of Southwest Papua. Specifically, the study examines the influence of basal area, tree density, and canopy cover on litter biomass production and associated carbon

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accumulation at the plot scale. Although agroforestry has been widely recognized for its climate mitigation potential, empirical assessments linking vegetation structural attributes, litter biomass production, and litter-derived carbon stocks remain limited, particularly in tropical community-managed agroforestry systems. We hypothesize that vegetation structural complexity, particularly stand basal area, exerts a stronger influence on litter-derived carbon inputs than tree density or canopy cover. By integrating vegetation structure and litter carbon dynamics within a single analytical framework, this study contributes new empirical evidence from an underrepresented tropical region and provides insights relevant to carbon accounting and climate change mitigation strategies in community-managed agroforestry landscapes.

MATERIALS AND METHODS

The study was conducted in two villages representing traditional agroforestry systems in Sorong Regency, Southwest Papua, namely Baingkete and Klayili. Both sites are located within lowland tropical ecosystems that experience a humid climate and support high levels of biological diversity. The study area lies between approximately 0°52′–1°10′ S latitude and 131°10′–131°20′ E longitude. Elevation across the sites ranges from 20 to 80 m above sea level, with mean annual precipitation exceeding 2,500 mm. Agroforestry management in both villages is based on the integration of subsistence crops, fruit-bearing trees, and perennial cash crops within a single land-use system. The dominant tree species include *Durio zibethinus*, *Myristica fragrans*, *Cocos nucifera*, and *Theobroma cacao*, which collectively form structurally complex stands typical of traditional agroforestry practices in the region.

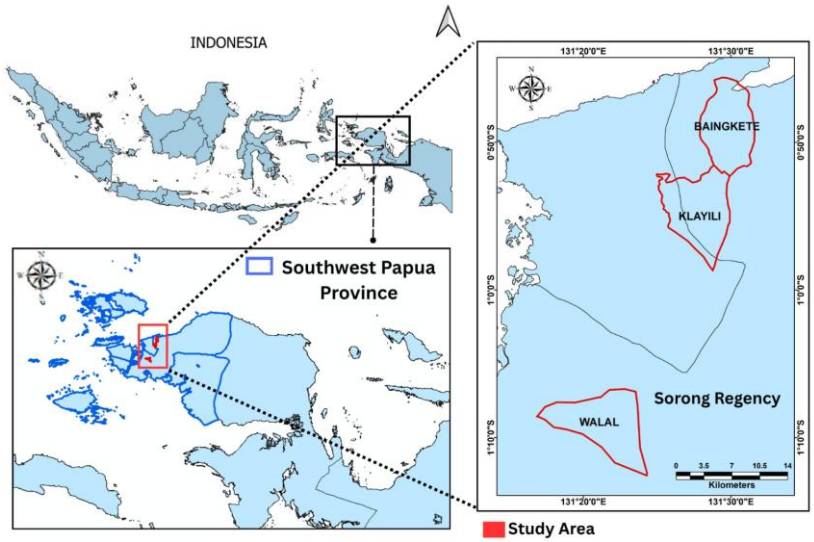


Figure 1. Study Area

Vegetation Sampling

Vegetation structure was measured in 30 square plots of 20 × 20 m systematically established across the two sites (15 plots in each location). Within each plot, all trees with a diameter at breast

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height (DBH) ≥ 10 cm were identified and recorded to species level and their DBH recorded. The following structural variables were computed:

Tree density (ind/ha):

$$D = \frac{N}{A} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

where N = number of trees in the plot, A = plot area (ha).

Basal area (m²/ha):

$$BA = \sum\left(\frac{\pi \cdot DBH^2}{4}\right) \times \frac{1}{A} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

where DBH = tree diameter at 1.3 m height (cm), converted to m² and standardized per hectare.

The Importance Value Index (IVI) was calculated by summing the relative density, relative frequency, and relative dominance of each species. Canopy cover (%) was measured using a spherical densiometer at four corners and the center of each plot, and the values were averaged to obtain plot-level canopy closure.

Litter Sampling

Litter biomass was collected from a 1 × 1 m subplot established within each 20 × 20 m vegetation plot. All litter material within the subplot was harvested, weighed fresh, and subsequently oven-dried to constant weight. Biomass values were initially expressed on an area basis (kg m^{-2}) and subsequently scaled to a hectare equivalent by multiplying by 10,000 m^2 ha^{-1}. Carbon stock was then estimated using the IPCC (2006) conversion factor of 0.47 for dry biomass.

Plot 5	Plot 6	Plot 15	Plot 16	Plot 25	Plot 26
Plot 4	Plot 7	Plot 14	Plot 17	Plot 24	Plot 27
Plot 3	Plot 8	Plot 13	Plot 18	Plot 23	Plot 28
Plot 2	Plot 9	Plot 12	Plot 19	plot 22	Plot 29
Plot 1	Plot 10	Plot 11	Plot 20	Plot 21	Plot 30

Figure 2. Grid Sampling

Litter biomass per plot (kg) was estimated using the following equation:

$$B = B_f \times \frac{B_d}{B_c} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (3)$$

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where:
B = litter biomass (kg/plot),
Bf = total fresh weight of litter (kg),
Bd = oven-dry weight of sub-sample (kg),
Bc = fresh weight of sub-sample (kg).
The biomass per plot was scaled up to a per hectare basis using:

$$B_{ha} = \frac{B}{A_p} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (4)$$

where A_p = plot area (ha).

Carbon Estimation

Litter carbon content was estimated using the IPCC (2006) default factor of 0.47 for dry biomass:

$$C = B \times 0.47 \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (5)$$

where:

C = carbon stock (kg/plot),

B = dry biomass (kg/plot).

Carbon per hectare was then calculated as:

$C_{ha} = \frac{C}{A_p}$ and expressed in ton C ha^{-1}. .....(6)

Data Analysis

Descriptive statistics (minimum, maximum, mean, median, and standard deviation) were used to summarize biomass and carbon stock data. Litter biomass was categorized into three classes: low (<0.7 kg), medium (0.7–1.2 kg), and high (>1.2 kg). To evaluate the relationships between vegetation structure and litter biomass, Pearson's correlation analysis was applied for three vegetation attributes: tree density, basal area, and canopy cover. Additionally, simple linear regression analysis was conducted to assess the strength and direction of these relationships. All statistical analyses were performed using IBM SPSS Statistics version 25.0. Statistical significance was determined at $p < 0.05$. Data visualization and descriptive summaries were cross-checked in Microsoft Excel 2021 to ensure accuracy.

RESULT AND DISCUSSION

Traditional agroforestry systems in Baingkete and Klayili exhibited a complex multistrata vegetation structure resembling that of secondary tropical forests. High regeneration densities ranging from 6,750 to 9,150 individuals ha^{-1} indicate continuous recruitment processes and suggest that these agroforestry systems maintain long-term stand persistence. Regeneration was dominated by economically valuable tree species, including *Myristica fragrans*, *Syzygium aromaticum*, *Lansium domesticum*, and *Canarium commune*, reflecting the integration of ecological and livelihood functions within traditional land-use practices.

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The observed regeneration pattern suggests that local management practices support both species replacement and stand continuity. Continuous recruitment is an important indicator of ecosystem resilience because it enables vegetation recovery following natural disturbances and harvesting activities. Similar patterns have been reported in tropical agroforestry systems where sustained regeneration contributes to long-term ecological stability and adaptive capacity under changing environmental conditions (FAO, 2022; Sayer *et al*., 2020).

Vertical vegetation analysis identified four distinct canopy strata, consisting of an upper canopy (33–39 m), middle canopy (20–30 m), sub-canopy (4–20 m), and understory layer (1–4 m). The upper canopy was dominated by *Durio zibethinus*, while *Cocos nucifera* and mature durian trees formed the middle canopy. The sub-canopy was primarily composed of nutmeg, clove, langsat, and cempedak, whereas the understory layer contained seedlings, saplings, and shrub vegetation. This stratified structure enhances light-use efficiency, reduces direct rainfall impact on the soil surface, and promotes favorable microclimatic conditions for litter accumulation and decomposition.

The presence of multiple canopy layers indicates a high degree of structural complexity, a characteristic frequently associated with increased biomass production, improved nutrient cycling, and greater carbon sequestration potential. Such vegetation architecture enables agroforestry systems to perform ecological functions comparable to those of natural secondary forests while simultaneously providing economic benefits to local communities.

Table 1. Stand structural characteristics of traditional agroforestry systems in Baingkete and Klayili villages

Variable	Unit	Baingkete	Klayili
Tree density	ind ha^{-1}	800	620
Basal area	m^2 ha^{-1}	132.4	70.1
Regeneration density (sapling–seedling)	ind ha^{-1}	6,750	9,150
Canopy cover	%	85.17	85.00

Table 1 shows clear differences in vegetation structure between the two traditional agroforestry systems. Baingkete exhibited higher tree density (800 individuals ha^{-1}) and substantially greater basal area (132.4 m^2 ha^{-1}) than Klayili (620 individuals ha^{-1} and 70.1 m^2 ha^{-1}, respectively). The markedly larger basal area in Baingkete indicates the presence of more mature and larger-diameter trees, suggesting greater biomass accumulation and higher carbon storage potential.

Basal area is widely recognized as an effective indicator of stand development because it integrates both tree size and stand stocking. The nearly twofold difference in basal area between Baingkete and Klayili suggests that tree growth and stand maturation contribute more strongly to structural development than stem abundance alone. This distinction becomes particularly important in agroforestry systems where large canopy trees often represent the principal source of biomass production and litterfall input.

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In contrast, Klayili exhibited higher regeneration density (9,150 individuals ha^{-1}) than Baingkete (6,750 individuals ha^{-1}). This pattern indicates more active recruitment processes and may reflect a younger stand condition or a greater proportion of recently established individuals. High regeneration density is generally associated with strong recovery capacity and future stand development, suggesting that Klayili possesses considerable potential for biomass accumulation as the stand matures.

Canopy cover exceeded 85% at both sites, indicating that despite differences in stand structure, the two agroforestry systems maintain similarly dense canopy conditions. Dense canopy closure plays an important ecological role by regulating microclimate, reducing soil moisture loss, and enhancing litter retention on the forest floor. The similarity in canopy cover between sites further suggests that differences in litter production and carbon accumulation are likely driven more by stand structural attributes, particularly basal area and tree size distribution, than by canopy closure itself.

Overall, the combination of high canopy cover, substantial regeneration, and large basal area confirms that both agroforestry systems possess structural characteristics comparable to those of mature secondary tropical forests. However, the greater basal area observed in Baingkete indicates a more advanced stage of stand development, whereas the higher regeneration density in Klayili reflects stronger recruitment dynamics and future growth potential.

The structural differences observed between Baingkete and Klayili are further reflected in the vertical arrangement of vegetation layers. Canopy stratification provides important ecological information because it influences light interception, biomass allocation, litter production, and nutrient cycling processes. In traditional agroforestry systems, the presence of multiple canopy layers enhances resource-use efficiency and contributes to ecosystem stability by distributing ecological functions across different vegetation strata.

Table 2. Canopy Stratification and Ecological Functions of Traditional Agroforestry Systems

Canopy Layer	Height (m)	Presence (Baingkete)	Presence (Klayili)	Dominant Species	Ecological Role
Regeneration (sapling–seedling)	–	Present	Present	*Myristica fragrans*, *Eugenia aromatica*, *Lansium domesticum*, *Canarium commune*	Ensures stand continuity and resilience
A (Upper canopy)	33–39	Present	Present	*Durio zibethinus*	Microclimate control; major litter input
B (Mid canopy)	20–30	Present	Present	*Cocos nucifera*, *Durio zibethinus*	Maintains canopy continuity and shading
C (Sub-canopy)	4–20	Present	Present	*Myristica fragrans*, *Eugenia aromatica*, *Lansium*	Regulates light and nutrient cycling

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Canopy Layer	Height (m)	Presence (Baingkete)	Presence (Klayili)	Dominant Species	Ecological Role
				domesticum, *Artocarpus champeden*	
D (Understory)	1–4	Present	Present	Young *Myristica fragrans*, shrubs	Protects soil surface; supports regeneration
Overall canopy cover	–	85.17%	85.00%	–	Maintains soil moisture and reduces erosion

Table 2 demonstrates that both agroforestry systems possess a well-developed multistrata canopy structure consisting of regeneration, understory, sub-canopy, mid-canopy, and upper-canopy layers. The occurrence of all vegetation strata in both locations indicates a high degree of structural complexity and suggests that ecological functions are distributed throughout the vertical profile of the stand.

The upper canopy layer, dominated primarily by *Durio zibethinus*, represents the principal source of biomass production and litterfall input. Large canopy trees contribute substantial quantities of leaves, twigs, flowers, and fruits to the forest floor, thereby providing a continuous supply of organic matter for decomposition and soil carbon formation. In tropical ecosystems, dominant canopy trees often account for a disproportionately large share of litter production because of their extensive crown dimensions and greater biomass turnover.

The middle canopy, composed mainly of *Cocos nucifera* and mature durian trees, plays an important role in maintaining canopy continuity and regulating light penetration. Continuous canopy cover moderates temperature fluctuations, reduces evapotranspiration, and creates favorable microclimatic conditions for litter accumulation and decomposition. Such conditions enhance nutrient retention and support efficient carbon cycling within agroforestry ecosystems.

The sub-canopy layer, dominated by *Myristica fragrans*, *Syzygium aromaticum*, *Lansium domesticum*, and *Artocarpus champeden*, contributes to vertical structural diversity and complements the ecological functions of the upper canopy. Species occupying this layer provide additional litter inputs while improving spatial distribution of biomass within the stand. The coexistence of multiple productive species across different canopy levels increases system resilience and reduces dependence on a single vegetation stratum.

At the lower level, the understory and regeneration layers play a critical role in maintaining stand continuity. The presence of abundant seedlings and saplings indicates active recruitment processes and ensures long-term replacement of mature individuals. Regeneration not only supports future biomass accumulation but also contributes to the persistence of carbon sequestration functions over time. High regeneration density observed in both sites suggests that these agroforestry systems possess strong recovery capacity and ecological resilience.

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The overall canopy cover exceeding 85% in both locations further confirms the integrity of the vegetation structure. Dense canopy closure promotes litter retention, protects soil surfaces from direct rainfall impact, and maintains favorable moisture conditions for microbial activity. These factors collectively enhance the conversion of litter biomass into soil organic matter and contribute to long-term carbon stabilization.

From a carbon-cycle perspective, the multistrata canopy architecture observed in Baingkete and Klayili provides an important ecological mechanism linking vegetation structure with litter-derived carbon accumulation. The combination of large upper-canopy trees, productive intermediate strata, and continuous regeneration creates a sustained flow of organic matter from vegetation to soil. This finding supports the hypothesis that structurally complex agroforestry systems function similarly to secondary tropical forests in maintaining carbon cycling and ecosystem productivity.

The estimated litter carbon stock of 4.28 ton C ha^{-1} falls within the range reported for mature agroforestry systems in humid tropical regions. Studies conducted in Indonesia and Southeast Asia have reported litter carbon values ranging from 3.0 to 6.0 ton C ha^{-1}, indicating comparable ecological functioning between traditional agroforestry and natural secondary forests (Roshetko *et al*., 2013; Hairiah *et al*., 2019; Tumuhe *et al*., 2020). This finding highlights the significant role of community-managed agroforestry systems in supporting landscape-level carbon dynamics.

Table 3 summarizes the variation in litter biomass across the 30 observation plots established within traditional agroforestry systems in Southwest Papua. Litter biomass ranged from 0.416 to 1.810 kg $plot^{-1}$, with a mean value of 0.886 kg $plot^{-1}$ and a median of 0.866 kg $plot^{-1}$. The close agreement between mean and median values indicates a relatively symmetrical distribution of observations and suggests the absence of extreme outliers influencing overall biomass estimates.

The coefficient of variation (36.5%) indicates moderate spatial variability in litter biomass among plots. Such variability is expected in traditional agroforestry systems because vegetation structure, tree size distribution, species composition, and canopy architecture differ among management units. Previous studies have demonstrated that litter production in tropical agroforestry systems is strongly influenced by stand structural heterogeneity, particularly variations in basal area and canopy stratification (Bhat *et al*., 2014; Negash & Starr, 2021).

The observed mean litter biomass is comparable to values reported for mature agroforestry systems in humid tropical regions. Hairiah *et al*. (2019) reported litter biomass values ranging from approximately 6–10 t ha^{-1} in multistrata agroforestry systems in Indonesia, while Roshetko *et al*. (2013) documented similar litter accumulation patterns in smallholder agroforestry landscapes across Southeast Asia. Such consistency suggests that the agroforestry systems examined in this study maintain ecosystem processes comparable to those found in other well-developed tropical agroforests.

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Ecologically, the moderate variability observed among plots reflects differences in stand development and vegetation structural complexity. Plots characterized by larger basal areas and mature canopy trees likely contributed greater quantities of litter through increased leaf production and biomass turnover. Conversely, plots dominated by younger individuals or smaller-diameter trees tended to exhibit lower litter accumulation. Similar relationships between stand maturity and litter production have been widely documented in tropical forests, where larger trees contribute disproportionately to annual litterfall and nutrient return (Malhi *et al*., 2011; Sayer *et al*., 2020).

The relatively high average litter biomass observed in this study indicates a substantial transfer of organic matter from vegetation to soil. Litterfall represents a major pathway through which carbon and nutrients enter the soil system, supporting microbial activity, soil organic matter formation, and long-term carbon sequestration (Vitousek & Sanford, 1986; Kumar & Nair, 2011). Consequently, the recorded biomass values suggest that traditional agroforestry systems in Southwest Papua function as important reservoirs of organic matter and play a significant role in sustaining ecosystem carbon cycling.

Table 3. Descriptive statistics of litter biomass across 30 plots

Parameter	Value
Minimum (kg)	0.416
Maximum (kg)	1.810
Mean (kg)	0.886
Median (kg)	0.866
Standard deviation (kg)	0.344
Coefficient of variation (%)	36.5

Although descriptive statistics provide an overall assessment of litter biomass variation, categorizing biomass into different classes offers additional insight into the spatial distribution of organic matter inputs across the landscape. Such classification helps identify dominant productivity patterns and facilitates interpretation of ecosystem functioning within traditional agroforestry systems.

Table 4. Litter biomass distribution categories

Biomass Category	Range (kg)	Number of Plots	Percentage (%)
Low	< 0.7	10	33.3
Medium	0.7–1.2	12	40.0
High	> 1.2	8	26.7
Total	-	30	100

The distribution of litter biomass across the study plots indicates a relatively stable pattern of organic matter input within the traditional agroforestry systems. Most plots were classified in the medium biomass category (40%), followed by low (33.3%) and high (26.7%) categories, suggesting that litter production is maintained at a moderate and balanced level across the landscape. This pattern reflects the influence of multistrata canopy structures that enable continuous litterfall from

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different vegetation layers throughout the year. In structurally complex agroforestry systems, variations in species composition and phenology among canopy strata contribute to sustained organic matter input, which supports nutrient cycling and soil fertility maintenance (Kumar & Nair, 2011; Hairiah *et al*., 2019). Similar observations have been reported in tropical agroforestry landscapes where moderate litter biomass indicates stable ecosystem functioning and consistent carbon input to the soil system (Sayer *et al*., 2020; Mbow *et al*., 2021).

Ecologically, the presence of both high and low biomass plots suggests spatial variability related to stand structure, particularly tree size distribution and basal area. Plots with higher litter biomass are likely associated with larger trees and more developed canopy layers, which contribute greater leaf turnover and biomass production, while lower biomass plots may represent younger stands or areas with lower structural complexity. Previous studies demonstrate that basal area and stand maturity strongly influence litterfall dynamics and ecosystem productivity in tropical forests and agroforestry systems (Malhi *et al*., 2011; Poorter *et al*., 2021). Therefore, the dominance of the medium litter biomass class observed in this study supports the broader finding that traditional agroforestry systems in Southwest Papua function as structurally stable ecosystems comparable to secondary tropical forests. This result provides important empirical evidence that community-managed agroforestry landscapes can sustain continuous nutrient cycling and contribute to landscape-level carbon dynamics in humid tropical regions.

Table 4 shows that litter biomass was predominantly concentrated within the medium category (0.7–1.2 kg plot^{-1}), representing 40% of the total observation plots. The remaining plots were distributed between the low biomass category (<0.7 kg plot^{-1}; 33.3%) and the high biomass category (>1.2 kg plot^{-1}; 26.7%). This distribution pattern indicates that most agroforestry stands maintain moderate and relatively stable rates of litter production. The predominance of the medium biomass class suggests that organic matter inputs are distributed relatively evenly across the study area. In multistrata agroforestry systems, continuous litterfall occurs throughout the year because different species exhibit varying phenological cycles. Consequently, litter production is less concentrated in short seasonal pulses and instead occurs more consistently over time, contributing to stable nutrient cycling and carbon transfer processes (Kumar & Nair, 2011; Sari *et al*., 2022).

The occurrence of plots within the high biomass category reflects localized areas characterized by greater structural development, particularly larger tree dimensions and higher basal area values. Mature canopy trees generally produce greater quantities of litter owing to larger crown sizes, increased leaf biomass, and higher rates of biomass turnover (Malhi *et al*., 2011). Such plots may function as important hotspots of carbon input, contributing disproportionately to soil organic matter accumulation and nutrient availability within the agroforestry landscape. Conversely, plots classified within the low biomass category likely represent stands with lower structural complexity, younger tree cohorts, or reduced canopy development. Lower litter production in these plots does not necessarily indicate ecological degradation but may instead reflect

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differences in successional stage or management history. Similar spatial heterogeneity in litter accumulation has been reported across tropical agroforestry systems where stand age and vegetation structure strongly influence organic matter dynamics (Bhat *et al*., 2014; Negash & Starr, 2021).

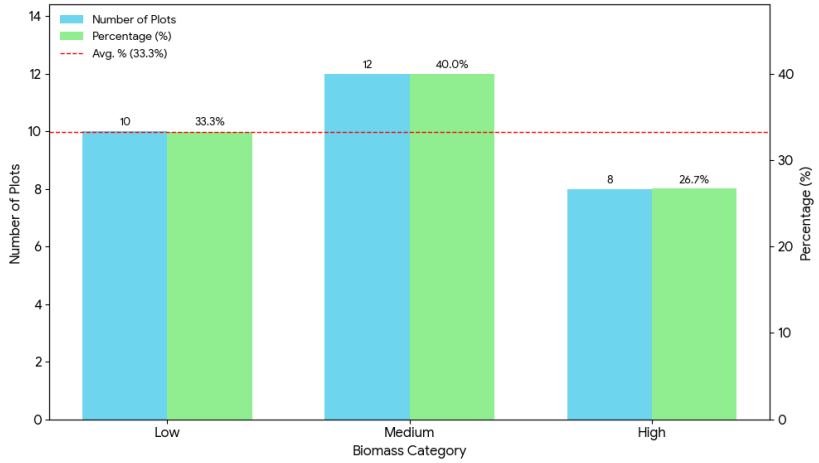


Figure 3. Distribution of litter biomass Categorie in Traditional agroforestry system in Sorong

The figure illustrates the distribution of litter biomass across 30 plots, classified into three categories: Low (<0.7 kg), Medium (0.7–1.2 kg), and High (>1.2 kg). The blue bars represent the *number of plots*, while the green bars indicate the *percentage of plots* within each category. The red dashed line marks the average percentage value (33.3%), serving as a reference threshold for balanced distribution.

The medium biomass category dominates the distribution, accounting for 40% of the total plots (12 plots), followed by the low category (33.3%, 10 plots) and the high category (26.7%, 8 plots). This pattern reflects a relatively stable litter production rate across most agroforestry sites, with the majority of plots maintaining moderate biomass levels. The predominance of the medium class suggests that traditional agroforestry systems in Southwest Papua sustain consistent litterfall through well-developed multi-strata canopy structures that regulate microclimatic conditions and enhance continuous organic matter input.

Table 5 highlights clear differences in vegetation structure between the two traditional agroforestry systems. Baingkete exhibited higher tree density (800 individuals ha^{-1}) and nearly twice the basal area recorded in Klayili (132.4 versus 70.1 m^2 ha^{-1}), indicating a more mature stand structure characterized by larger trees and greater biomass accumulation. In contrast, Klayili was characterized by lower stand density and basal area, suggesting a relatively younger stand condition or a greater proportion of smaller-diameter individuals. The substantial difference in basal area between sites is ecologically important because basal area integrates both tree size and stand stocking and is widely recognized as a strong indicator of stand development and biomass accumulation. Larger basal area generally reflects greater canopy volume, higher photosynthetic capacity, and increased potential for litter production (Malhi *et al*., 2011; Poorter *et al*., 2021).

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Despite these structural differences, canopy cover remained consistently high at both locations (>78%), indicating that both agroforestry systems maintain relatively closed canopy conditions. Dense canopy cover contributes to microclimatic stability, promotes litter retention, and supports continuous nutrient cycling processes (Ong *et al*., 2019; Widyastuti *et al*., 2020). These findings suggest that although Baingkete and Klayili differ in stand development and vegetation structure, both systems possess sufficient structural complexity to support ecological functions commonly associated with mature tropical agroforestry systems. Such structural characteristics provide the ecological foundation for sustained litter production and carbon cycling across the study landscape.

Table 5. Comparative vegetation structure of Traditional agroforestry system

Location	Dominant Species	Tree Density (ind ha^{-1})	Basal Area (m^2 ha^{-1})	Canopy Cover (%)
Baingkete	*Durio zibethinus*, *Myristica fragrans*, *Cocos nucifera*	800	132.4	78–85.2
Klayili	*Durio zibethinus*, *Theobroma cacao*, *Myristica fragrans*	620	70.1	78–85.0

The observed variation in vegetation structure among agroforestry plots suggests that stand attributes may play an important role in regulating litter biomass production. Structural variables such as tree density, basal area, and canopy cover influence biomass allocation, litterfall dynamics, and organic matter accumulation through their effects on stand productivity and resource-use efficiency. To quantify these relationships, correlation analyses were conducted to evaluate the strength and direction of associations between vegetation structural attributes and litter biomass across the study plots.

Table 6. Correlation and regression between vegetation structure and litter biomass

Variable	Regression Equation	r	R^2	p-value	Interpretation
Tree Density	y = 0.45 + 0.00055x	0.62	0.38	<0.01	Moderate positive
Basal Area	y = 0.40 + 0.0035x	0.79	0.62	<0.001	Strong positive
Canopy Cover	y = 0.52 + 0.0040x	0.48	0.23	<0.05	Weak–moderate positive

Table 6 presents the correlation coefficients between vegetation structural attributes and litter biomass across the 30 agroforestry plots. All three structural variables exhibited positive and statistically significant relationships with litter biomass, indicating that increases in vegetation structural complexity are associated with greater organic matter accumulation. Basal area showed the strongest relationship with litter biomass ($r = 0.88$, $p < 0.001$), followed by canopy cover ($r = 0.82$,

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$p < 0.001$) and tree density ($r = 0.79$, $p < 0.001$). The consistently high correlation coefficients indicate that vegetation structure is a major determinant of litter production in traditional agroforestry systems.

The strong relationship between basal area and litter biomass highlights the importance of stand maturity in regulating carbon inputs. Basal area integrates both tree size and stand stocking and therefore reflects the cumulative capacity of vegetation to produce biomass. Larger trees generally possess greater crown area, higher leaf biomass, and increased rates of biomass turnover, resulting in larger quantities of litterfall reaching the forest floor (Malhi *et al*., 2011; Poorter *et al*., 2021). Similar findings have been reported in tropical forest and agroforestry ecosystems where basal area consistently emerges as one of the strongest predictors of litter production and aboveground carbon accumulation.

Canopy cover also exhibited a strong positive relationship with litter biomass. Dense canopy closure enhances leaf production while simultaneously reducing exposure of litter to direct solar radiation and wind disturbance. Furthermore, closed canopies create stable microclimatic conditions characterized by lower temperature fluctuations and higher humidity, which promote litter retention and decomposition processes (Widyastuti *et al*., 2020; Ong *et al*., 2019).

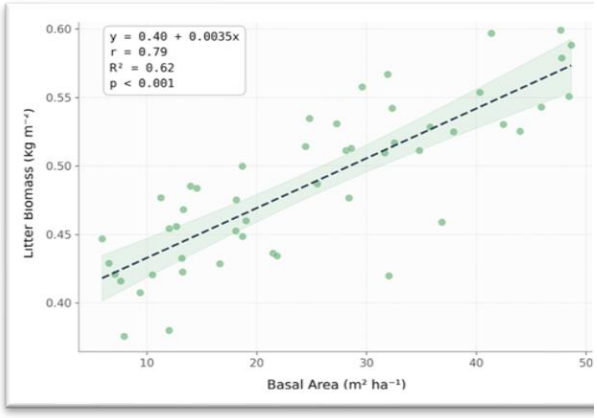


Figure 4a. Relationship between Basal Area and Litter Biomass

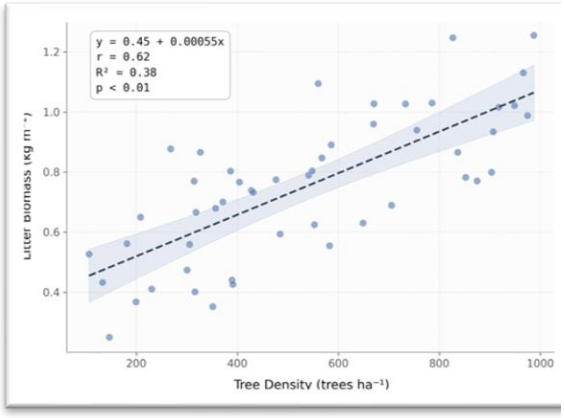


Figure 4b. Relationship between Tree Density and Litter Biomass

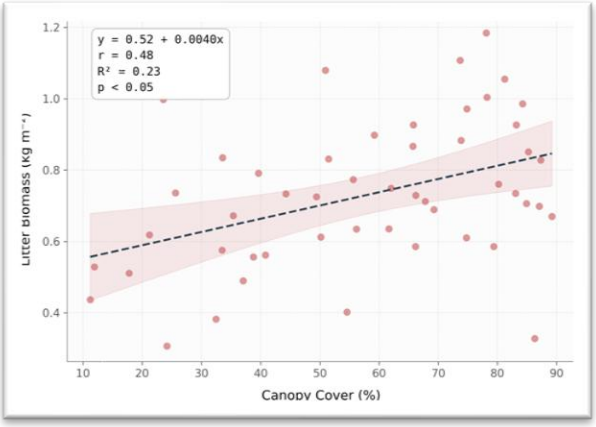


Figure 4c. Relationship between Canopy Cover and Litter Biomass.

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The strong positive relationship observed between basal area and litter biomass (Figure 4a) indicates that stand size structure is a major determinant of organic matter inputs in traditional agroforestry systems. Basal area reflects the cumulative cross-sectional area of tree stems and therefore integrates information on both tree size and stand development. Larger basal area values are generally associated with greater aboveground biomass, more extensive crown architecture, and increased leaf area, all of which contribute to higher litterfall production. As trees mature, the accumulation of leaves, twigs, flowers, fruits, and senescent tissues increases, resulting in greater quantities of litter deposited on the soil surface. Consequently, agroforestry plots characterized by high basal area tend to exhibit enhanced carbon inputs through litter production and improved nutrient cycling processes (Malhi *et al*., 2011; Chave *et al*., 2014).

From an ecological perspective, basal area is often considered a superior predictor of ecosystem productivity because it captures variations in tree dimensions that are not reflected by stem density alone. Several studies in tropical forests have demonstrated that stands dominated by large-diameter trees contribute disproportionately to biomass production and carbon accumulation. Large trees possess greater photosynthetic capacity, larger crowns, and higher biomass turnover rates, resulting in increased litterfall and carbon transfer to the soil subsystem (Poorter *et al*., 2021; Sullivan *et al*., 2017). Therefore, the strong association between basal area and litter biomass observed in this study suggests that maintaining mature trees within agroforestry systems is essential for sustaining long-term organic matter inputs, enhancing soil fertility, and supporting ecosystem carbon dynamics.

Tree density showed a significant positive relationship with litter biomass (Figure 4b), indicating that the number of trees per unit area influences the amount of organic material returned to the soil. Higher tree density increases the total leaf-bearing surface within a stand and consequently enhances the production of litterfall. In agroforestry systems, a greater number of individual trees can contribute to continuous inputs of leaves, small branches, reproductive structures, and other plant residues throughout the year. This continuous litter deposition plays a vital role in maintaining soil organic matter, improving nutrient availability, and supporting microbial activity (Hairiah *et al*., 2020; Jose, 2009). The positive association found in this study therefore highlights the contribution of stand stocking to ecosystem productivity and nutrient cycling.

However, the relationship between tree density and litter biomass was weaker than that observed for basal area, suggesting that stem abundance alone does not fully determine litter production. In densely stocked stands, competition for light, water, and nutrients may limit individual tree growth and reduce leaf biomass per tree. Consequently, stands with high tree density but small-diameter trees may produce less litter than stands containing fewer but larger individuals. Similar patterns have been reported in tropical agroforestry and secondary forest ecosystems, where litter production is more strongly influenced by tree size and crown development than by stem

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numbers alone (Paudel *et al*., 2015; Sayer *et al*., 2020). This finding indicates that both stand density and tree growth characteristics should be considered when evaluating ecosystem productivity and carbon inputs.

Canopy cover also exhibited a positive and significant relationship with litter biomass (Figure 4c), demonstrating the importance of crown development in regulating organic matter accumulation. Dense canopy cover generally reflects greater leaf area index and higher foliage abundance, which directly increase the amount of litter generated through leaf senescence and branch turnover. In agroforestry ecosystems, extensive canopy cover enhances primary productivity by maximizing light interception and photosynthetic activity, thereby promoting biomass production and litterfall generation. Furthermore, greater canopy closure contributes to the maintenance of favorable microclimatic conditions, including reduced temperature fluctuations and increased air humidity, which facilitate litter accumulation on the forest floor (Ong *et al*., 2019; Kumar & Nair, 2011).

Despite its positive influence, canopy cover explained a smaller proportion of variation in litter biomass compared with basal area and tree density. This outcome may be attributed to the fact that canopy cover primarily describes horizontal crown occupancy rather than actual biomass volume or tree size. Different agroforestry stands may exhibit similar canopy closure levels while differing substantially in species composition, stem dimensions, and biomass accumulation. As a result, canopy cover alone may not fully capture variations in litter production among plots. Similar observations have been reported in tropical agroforestry systems where canopy structure influences litter dynamics indirectly through its effects on productivity, microclimate, and decomposition processes (Sileshi *et al*., 2014; Udawatta *et al*., 2019).

Overall, the findings demonstrate that vegetation structural complexity constitutes the primary ecological mechanism regulating litter biomass accumulation in traditional agroforestry systems of Southwest Papua. Although tree density, basal area, and canopy cover all contributed positively to litter production, basal area emerged as the most influential structural attribute because it integrates stand stocking, tree size, crown development, and stand maturity simultaneously. Larger trees possess greater leaf area, more extensive crown architecture, and higher biomass turnover rates, resulting in substantially greater organic matter inputs to the forest floor. The multistrata canopy structure observed in both Baingkete and Klayili further enhances this process by ensuring continuous litterfall from multiple vegetation layers while maintaining favorable microclimatic conditions for litter retention and decomposition. Consequently, litter biomass accumulation is not determined solely by the number of trees or canopy closure, but rather by the combined effects of stand maturity and structural development represented by basal area. These findings support ecological theory that mature, structurally complex agroforestry systems function similarly to secondary tropical forests in sustaining nutrient cycling, soil organic matter formation, and carbon sequestration processes. Therefore, management strategies aimed at maintaining large-

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diameter trees and preserving multistrata stand structure are likely to provide the greatest long-term benefits for ecosystem productivity, soil fertility, and climate-change mitigation within community-managed agroforestry landscapes.

CONCLUSION

This study demonstrates that vegetation structural attributes strongly influence litter biomass production and litter-derived carbon accumulation in traditional agroforestry systems of Southwest Papua. Among the evaluated variables, basal area exhibited the strongest relationship with litter biomass, followed by canopy cover and tree density, indicating that stand maturity and structural complexity are key determinants of organic matter inputs to the soil. The results further reveal that multistrata agroforestry systems characterized by large-diameter trees, dense canopy cover, and continuous regeneration maintain stable litter production and support efficient carbon cycling processes. The strong positive relationships observed between vegetation structure and litter biomass suggest that structurally complex agroforestry systems can enhance nutrient turnover, sustain soil organic matter formation, and contribute to long-term carbon sequestration.

A major contribution of this study is the empirical evidence demonstrating that basal area serves as the most influential structural predictor of litter biomass within traditional agroforestry systems. This finding highlights the ecological importance of maintaining mature trees and canopy integrity as mechanisms for sustaining ecosystem productivity and carbon inputs. The study therefore provides quantitative support for integrating vegetation structural indicators into agroforestry-based carbon accounting and climate change mitigation strategies. From a practical perspective, the conservation and sustainable management of traditional agroforestry systems should prioritize the retention of large trees, maintenance of multistrata canopy structures, and promotion of natural regeneration processes. Such management approaches may simultaneously strengthen ecosystem resilience, maintain soil fertility, and enhance the contribution of agroforestry landscapes to national climate mitigation targets. Future research should expand spatial and temporal monitoring to evaluate seasonal litterfall dynamics, decomposition rates, and interactions between litter-derived carbon and soil organic carbon pools, thereby improving understanding of carbon cycling mechanisms in tropical agroforestry ecosystems. These findings reinforce the potential of traditional agroforestry systems as nature-based solutions that simultaneously support rural livelihoods, biodiversity conservation, and climate change mitigation in tropical landscapes.

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